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DOCUMENTATION FOR THE USAF SCHOOL OF AEROSPACE MEDICINE ALTITUDE DECOMPRESSION SICKNESS RESEARCH DATABASE

James T. Webb, Ph.D.
Scientific Aerospace Research Consulting (SARC), LLC
Under contract with Eagle Applied Sciences, LLC

AEROSPACE PHYSIOLOGY DIVISION

USAF School of Aerospace Medicine
USAFSAM/FEEP
2601 Louis Bauer Drive
Brooks City-Base, TX 78235-5130

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School of Aerospace Medicine
2513 Kennedy Circle
Brooks City-Base, TX 78235-5116

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_____//SIGNED//_____
Andrew D. Woodrow, Lt Col, USAF, BSC
Chief, Aerospace Physiology Division

_____//SIGNED//_____
James W. Weissmann, Col, USAF, BSC
Chief, Aerospace Medicine Education Division

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This report is designed to be a reference for Aerospace Researchers and Technicians in the US Air Force who are tasked to perform altitude decompression sickness (DCS) research. It contains information about the development, use, search, reporting, and query capabilities of the USAFSAM Altitude DCS Research Database. The database uses Microsoft™ Access 2003 and contains information on over 3000 subject-exposures that includes extensive data on venous gas emboli, symptom development, and, in conjunction with this document, detailed information on the activities performed during decompression.

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PREFACE

The purpose of this Special Report is to provide documentation for the altitude decompression sickness (DCS) research database developed at Brooks AFB, TX. The research data in the database came from altitude chamber research from 1983-2005 at Brooks AFB/City-Base under the auspices of the USAF School of Aerospace Medicine, the Armstrong Laboratory, and the Air Force Research Laboratory.

Use of this documentation with the data in the Altitude Decompression Sickness (DCS) Research Database should provide access to virtually all information that was recorded during more than 3000 subject-exposures conducted at Brooks.

James T. Webb, Ph.D.

Chamber “C” at Brooks AFB/City-Base, TX (above) was the site of all DCS research studies from 1960-2009.

DOCUMENTATION FOR THE USAF SCHOOL OF AEROSPACE MEDICINE ALTITUDE DECOMPRESSION SICKNESS RESEARCH DATABASE

SUMMARY

The purpose of this documentation is several-fold: 1) Provide information on decompression sickness (DCS) research methodology; 2) Provide documentation on how to access research results accomplished at Brooks AFB/City-Base from 1983 to 2005; and 3) Provide the necessary background to enable research using the USAFSAM Altitude DCS Research Database. It provides descriptions of activities and procedures suitable for inclusion in methodology sections of reports in conjunction with the Guide to Altitude Decompression Sickness Research (AFRL-SA-BR-SR-2009-0008), the published articles based on this resource (APPENDIX I), and other references in APPENDIX II. APPENDIX I shows both the utility and diversity of research protocol results contained in the database.

A good understanding of Microsoft™ Access 2003 structure and function is assumed. If the database is to be modified in any way, it is highly recommended that a backup copy be made and kept secure. Although data entry and retrieval has been made relatively easy via menu, drop-down lists, and explanations in this documentation, an understanding of the purpose of each protocol is necessary to properly utilize and interpret the results in the database. To that end, a description of each protocol is included to allow a better understanding of the limitations on subject population, test termination criteria (endpoints), and data acquisition.

To retain USAF standard date format, all dates are recorded as DayMonthYear using three-letter month abbreviations, e.g. 25Dec02 which is entered without the dashes that are placed in the date by an input mask of Microsoft™ Access. All paperwork records should also use this standard date format.

INTRODUCTION

The USAFSAM Altitude DCS Research Database (the database) is a relational, menu-driven, nine-table database which can produce reports and downloads to MSExcel 2003 workbooks on each protocol and/or profile with a few clicks of menu buttons. The database is, as of this writing, located on the USAFSAM server at (N:)\FE\FEA\Reference Project\References\DCS.mdb and is in Microsoft™ Access 2003 format. The initial screen presented upon opening the .mdb is shown below (**Fig 1**).

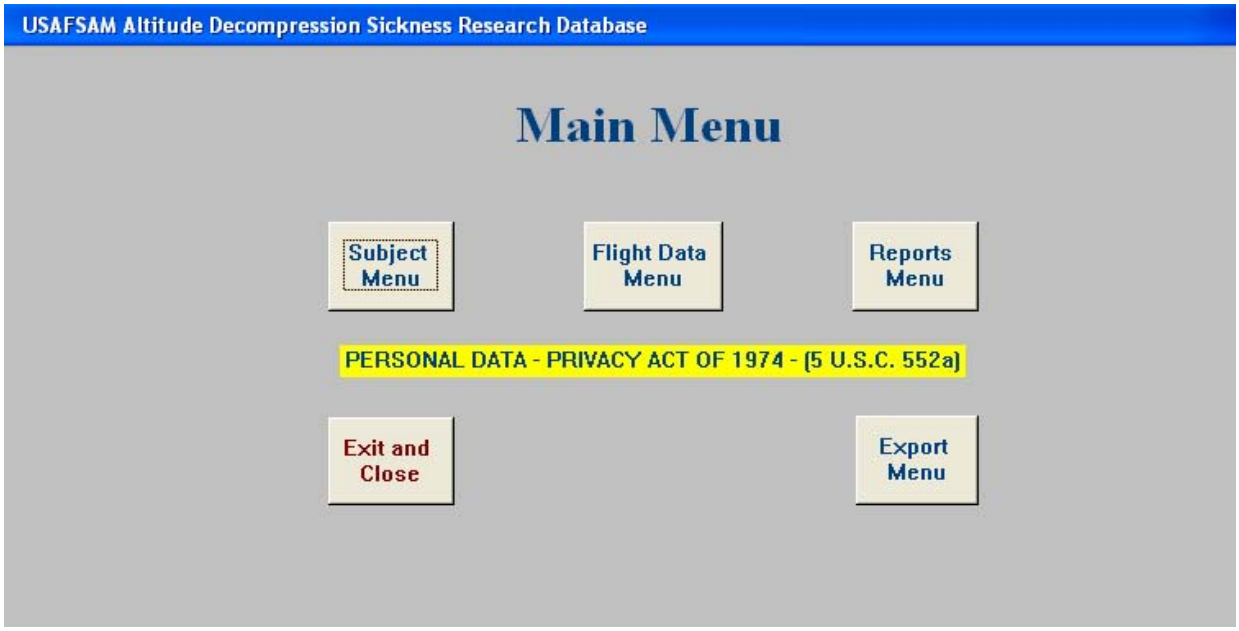

Fig 1. USAFSAM Altitude Decompression Sickness Research Database Main Menu

The multiple-table format of the database is efficient due to the variable number of entries in the tables for any given exposure or subject or study and the relationships between the tables. To reserve the maximum number of entries for the parameters in the tables would have made a very large database. The eight tables are: Subject, Injury, Flight, Segment, Bubbles, Symptoms, Medication, and Study Design. Each subject can participate in many Flights, several of which could be described by one Study Design. Each exposure has a discrete number, the automatically-assigned Man-Flight-Number (MFN), which may be associated with many or few Bubble records and several or no Symptom records. Each MFN will also have several segments describing the pressure changes and may have several breathing Gases. As time passes, each Subject may also acquire new Injuries and take different Medications. The relationships between these tables are defined and assigned to account for the temporal and pressure variables of each exposure and the resulting subject reactions so as to allow retrieval of the correct information at the correct command.

HISTORY

The database was created in the early 1980s to manage the large amount of data gathered from each subject exposure and provide a means of retrieving that data. It was on the UNIVAC computer (System 2000 database created, in part, by Bill Nixon of the Biostatistics Division) at the Human Resources Division (HRL), then transferred to the VAX 11-70 in USAFSAM. In 1998 it was converted to a desktop PC using Microsoft™ Access 97 under the Air Force Research Laboratory. The conversion to Microsoft™ Access allowed retrieval of information to become much easier and data entry to become more standardized.

After that transition, from 1999 thru 2002, a reorganization of the tables resulted in creation/deletion of several tables and formation of separate databases for tables not perceived to be of current or future research use. The Anthropometric table was deleted and the information incorporated into the Subject and Flight tables. The TimeOfBubbleGrade table was created, then deleted due to redundancy, propensity for double-entry data errors, and later availability of an adequate query for retrieval of the same data from the Bubble and Symptoms tables. The Experimental Medication was deleted since it was never used or planned to be used. The Hematologic table, data on blood analyses accomplished during the 8.3 psia study, was kept as a separate database (Hematologic.mdb) because no further data were being acquired. The Non-specific Medication table was renamed to become the Medication table. The Exercise RPE table, data on reports of perceived exertion during exercises performed during some exposures in the Model Validation (Short Title = MV) protocol was kept as a separate database (ExerciseRPE.mdb). The Urine Collection table, a table containing data on urine collection and analyses from late 1997 to early 2000, was never utilized for report production and was separated as a stand-alone database (UrineCollection.mdb). The Exercise table contained beginning and ending times of exercises performed during protocols until Oct2002 when it was deleted because the exercises were either performed as designated in the protocol and described herein or the exposure was terminated as “incomplete. Any data available in the Exercise table is more completely described herein or in the publications listed in Appendix I. The type of exercise performed is shown in the Study Design table. These independent databases may be linked to the database by the Man-Flight-Number field. This documentation does not contain further information on these independent databases due to the low likelihood they will ever be used.

DATABASE TABLES

The database has eight (8) tables: Bubble, Flight, Injury, Medication, Segment, Study Design, Subject, and Symptoms. The table names in the database are preceded by a lower-case "t" to designate their form for easier identification during some database operations and that "t" and other such identifiers are dropped in the following headings to allow easier reading of the Table of Contents. The descriptions in Design View of the tables are limited in size and many of the fields require additional information to include complete drop-down (Combo Box) listings of acceptable entries. Drop-down lists are used to assist with standardization, data entry, and ease of data retrieval. Some of the entries in the database were only pertinent to previously-completed studies and are therefore omitted from the current drop-down lists. However, descriptions of many possible entries are included here for clarification. The too-lengthy lists are shown below in the form they appear in Design View of the Combo Boxes' Properties, Row Source[1].

Detailed Report Table

This table (tDetailedReport) is created by update from the Make Table Query, qDetailedReportTable, run after validation of new data entries or after any change to the data. A criteria in this query stipulates that incomplete flights will not be included. There were 61 incomplete flights, hence a difference of 61 between the number of flights in the tFlight table and the number of flights in the tDetailedReport table. The tDetailedReport table is complex, as it is created from a series of tables and queries as outlined in Appendix 3. One reason for its complexity was the need to account for staged decompression profiles as used during several protocols. Since several of them resulted in VGE, VGE4, or, in particular, DCS prior to arrival at the planned exposure altitude, determination of the time of occurrence had to be adjusted to relate to the planned time of arrival at the planned exposure altitude. The adjustment was done by equations embedded in the queries which all made the assumption that, for a given profile, the subject would have arrived at the planned time at the planned exposure altitude. The derivation was based on the arrival time at the stage altitude and the planned time at the stage plus the time to climb to the planned exposure altitude. The result was a hypothetical time of arrival at the planned exposure altitude, but acceptable due to the minute-by-minute Test Plans which, if not followed within a minute or two, resulted in an incomplete exposure and lost data, albeit rarely. See Appendix 3 for the example.

This table can provide data on specific exposures, profiles, protocols, and a summary of the entire database is shown in Table 1 below.

[1] The quotes in MSAccess 2000 “”are, unfortunately, different from those in MSWord and Find and Replace will not correctly operate in MSAccess 2000 by cut-and-paste. This means each cut-and-paste quote must be replaced in MSAccess 2000 individually in the Row Source of each Combo Box Properties. A space has been added after each semicolon (;) in this document to allow for line breaks. The space is not required in MSAccess.

Table 1. DCS Database Summary

Parameter	N
Total number of protocols	26
Total number of protocol profiles	125
All completed subject-exposures	3007
Total completed subject-exposures	2946
Completed exposure days	2041
Completed subject exposures that involved DCS	1190
% of Completed subject exposures that involved DCS	40.4%
# of Subjects with a completed exposure	573
# of Subjects with a completed exposure and DCS	356
% of Subjects with a completed exposure and DCS	62.1%

Study Design Table
(tSTUDY DESIGN)

Protocol Title : Short Title and Synopsis fields

This field contains the full Protocol Title from the Protocol Title field and an abbreviated common name (Short Title) separated by a two dashes. Each protocol has a formal name that is shown on the IRB-approved protocol and on the Informed Consent Document (ICD). That name is listed in the Protocol Title field but is rarely used due to its length. A Short Title field was created to show the routine title used for planning, scheduling, and most conversations about the protocol. The *Synopsis* field after each Protocol Title : Short Title field is a short description including the protocol sponsor, purpose, and results. More detailed descriptions precede some of the Synopses.

Decompression Sickness (DCS) Protection Using a 100% Oxygen Pressure Suit Environment -- 100% Suit

The 100% Suit study was designed to provide a scientific basis for selection of the lowest pressure for extravehicular activity (EVA) pressure suits which will eliminate the hazards of decompression sickness (DCS) and severe bubbling (precordial Doppler bubble grades 3 and 4). Each subject was exposed one time so that a Probit analysis could establish a curve representing the population response to increased altitude of exposure without prebreathe. Since there were more male subjects available, the male exposures were started at the lowest altitude where DCS might be observed; 15,000 ft. The altitudes of exposure were based on the 8.3 psia study pressure and reduced 0.5 psia in succession. When the pressure reached 7.8 psia, female subjects were added since severe VGE (Grade 3 or higher; Spencer, 1976) had been observed in the male subjects at 7.8 psia (16,500 ft) and 7.3 psia (18,100 ft). The study was only designed to observe pressures down to 6.8 psia (19,800 ft) because it was believed that at least 50% DCS would be observed at that altitude based on observations of VGE at lower altitudes. Synopsis: The 100% Suit study was sponsored by NASA to determine the threshold of DCS without prebreathe. Results indicated a sigmoidal relationship between altitude and VGE and a DCS threshold above 19,800 ft as shown in Figure 1.

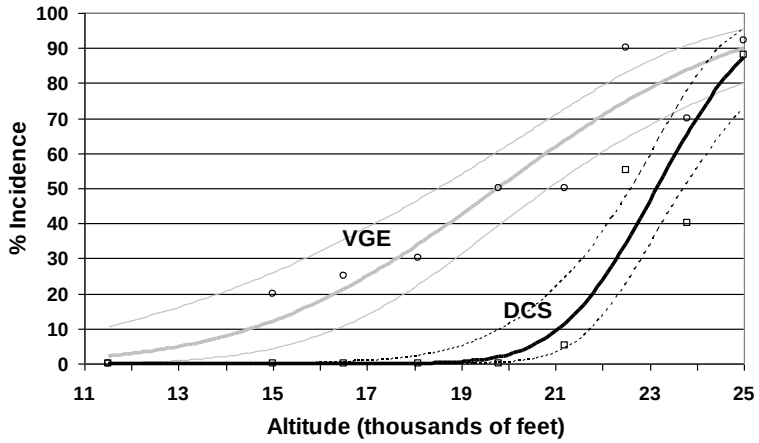

Fig 2. Sigmoidal relationship of exposure altitude and VGE and DCS incidence (from Webb et al. ,1998)

Decompression sickness on exposure to a simulated altitude of 35,000 feet -- 35K

The objective was to fulfill a request by the US Special Operations Command (USSOCOM) to investigate the decompression sickness (DCS) risk associated with airdrop missions from 35,000 feet. During such missions, exposed personnel include both the parachutists and the flight deck crew. Both groups may be considered to be at rest but, in addition, the parachutists are frequently exposed to a degree of exercise. In order to investigate the incidence of decompression sickness and latency prior to symptom onset, it was proposed to expose both male and female volunteers to a simulated altitude of 35,000 feet (179 mmHg) for up to 3 hours. A combination of rest and heavy exercise conditions were employed. The information obtained from this study was also used to help validate an Altitude DCS Risk Assessment Computer model. The model development was completed in 2004 with publication of the results (Pilmanis et al., 2004) at Brooks City Base and was designed for use in the operational environment.

Synopsis: This study was sponsored by USSOCOM and the results verified the limits for exposure for parachutists as stated in AFI 11-409 and provided input for development of the ADRAC model.

The Effect of Exposure to 40,000 feet on Altitude Decompression Sickness (DCS) Incidence -- 40K

The objective of this study was to determine the effect of human exposure to 40,000 feet on DCS incidence and time of onset of DCS symptoms. Information from this study was to be used in evaluating the need for future aircrew life support systems. The 90-min exposures after 90 min of prebreathe produced 47.5% DCS and 65.0% VGE.

Synopsis: This study was sponsored by the US Navy Smart Aircrew Integrated Life Support System (SAILSS) program and was designed to determine the effect of seated resting exposure to 40,000 ft on DCS incidence relative to 30,000 ft and 35,000 ft.

Decompression Sickness Protection Using an 8 psi Suit Environment -- 7.8 psia

The objective of this study was to evaluate use of a 50:50 N_2:O_2 environment as a potential breathing mix for extravehicular activity (EVA) from spacecraft. The DCS incidence was 2.7% with 186 subject-exposures performing moderate exercise for 6 h. Synopsis: This protocol was sponsored by NASA to investigate the effects of breathing a 50:50 N_2:O_2 during decompression at a potential EVA suit pressure. The mixed gas was used to avoid use of 100% oxygen which can create a fire hazard in spacecraft.

Decompression Sickness Protection Using an 8 psi Suit Environment -- 8.3 psia

The objective of this study was to evaluate use of a 50:50 N_2:O_2 environment as a potential breathing mix for extravehicular activity (EVA) from spacecraft. The DCS incidence was 3.1% with 31 subject-exposures performing moderate exercise for 6 h. Synopsis: This protocol was sponsored by NASA to investigate the effects of breathing a 50:50 N_2:O_2 during decompression at a potential EVA suit pressure. The mixed gas was used to avoid use of 100% oxygen which can create a fire hazard in spacecraft.

9.5 psia Bubble Threshold Validation -- 9.5 psia Validation

The objective of this study was to evaluate use of a 60:40 N_2:O_2 environment as a potential breathing mix for extravehicular activity (EVA) from spacecraft. The DCS incidence was 0% with 32 subject-exposures performing moderate exercise for 6 h. Synopsis: This protocol was sponsored by NASA to investigate the effects of breathing a 60:40 N_2:O_2 during decompression at a potential EVA suit pressure. The mixed gas was used to avoid use of 100% oxygen which can create a fire hazard in spacecraft.

The Effect of Adynamia on Altitude Decompression Sickness (DCS) Incidence -- Adynamia

The objective of this study was to determine if non-ambulatory altitude exposures produced the same level of DCS as ambulatory exposures with other conditions remaining the same. No difference in DCS incidence was observed, thus making ambulatory exposures in the database applicable to weightless conditions. However, there was a difference in the level of upper vs. lower-body joint pain which was evident statistically when many non-ambulatory vs. ambulatory studies' results were compared in Webb et al. (2005). See Balldin et al. (2002) and Webb et al. (2005) for details. Synopsis: The Adynamia Study was sponsored by NASA to investigate the effects of simulated weightlessness on incidence and severity of decompression sickness as related to extravehicular activity from the Space Shuttle or International Space Station. No difference in incidence of DCS was shown between control and simulated weightlessness conditions. VGE occurred more frequently during the control condition with bubble-releasing arm and leg movements.

Staged decompression with an argon-oxygen (ARGOX) breathing mixture to 3.5 psia -- ARGOX

The objective of this research was to provide data on decompression sickness (DCS) risk levels using a combination of procedures hypothesized to optimize denitrogenation. The procedures are designed to test a novel staged decompression procedure to 3.5 psia while breathing 100% oxygen, or a mixture of oxygen and argon, and include use of exercise-enhanced prebreathe. The data should provide a scientific

basis for future decisions regarding ways to improve mission accomplishment during extravehicular activity (EVA) and military spaceplane operations.
Synopsis: This study was sponsored by NASA to investigate the effects of a 62% Argon:38% Oxygen breathing gas during a staged-decompression to 3.5 psia and supported a future Mars mission.

The Effect of Ascent Rate to 40,000 feet on Decompression Sickness (DCS) Incidence -- Ascent Rate

The objective of this study was to determine the effect of altitude ascent rate on DCS incidence and time of onset of DCS symptoms. Although no statistical difference in DCS incidence was found when comparing results from 5,000 fpm vs. 80,000 fpm ascents to 40,000 ft (90-min prebreathe, 90-min exposure), there were a few more neurologic and respiratory symptoms following the faster ascent rate.
Synopsis: This study was sponsored by the US Navy SAILSS program and was designed to determine the effect of ascent rate on DCS incidence.

The Effect of an Air-breathing Break During Preoxygenation on Decompression Sickness Risk -- Break in Prebreathe

The objective of this study was to determine if air-breathing breaks in prebreathe would result in increased levels of DCS. The report is in review (Pilmanis et al., 2010).
Synopsis: The Break-In-Prebreathe Study is supported by AFRL and was designed to determine if a 10-min, 20-min or 60-min break in prebreathe after 30 min significantly degrades effectiveness of a 1-h total prebreathe. Results could be applied to the U-2 program and NASA extravehicular activity (Pilmanis et al., 2010; in review).

Bends Screening Index -- BSI

The BSI study was designed to "develop an innocuous method of testing for bends susceptibility." "a. Explore the bubble-bends relationship (of grade IV bubblers, what is the probability of developing clinical bends in a given individual at a specific altitude and exercise level?). b. Develop conditions for a screening test (what is the optimal altitude and exercise level that gives the best population spread of bends susceptibility to clearly separate "easy" from resistant "benders"?). c. Do the results of the susceptibility test apply equally well in classifying susceptibility at other levels of altitudes and exercise stress?

It is important to note that subjects who developed DCS at 30,000 ft (the highest altitude used in this study, although the protocol indicates 35,000 ft for the 5th exposure of each subject) were nominally exposed to 27,500 ft and, if again presenting with DCS, exposed to 25,000 ft with 33 of the 51 subjects participating in the study being exposed at least once to all three altitudes. Only 4 subjects were exposed at least once to all 4 altitudes used during the study, probably because the last altitude used, 22,500 ft, only had 3 of the exposures completed before exposures at the higher altitudes were completed; i.e. many of the subjects would have dropped out of the subject panel by that time. As subjects completed exposures to 30,000 ft and/or 27,500 ft, some were dropped from the study and new subjects were added to ensure a sufficient N was maintained. Two "non-susceptible" subjects, defined here as not developing DCS at 25,000 ft and either 30,000 ft or 27,500 ft, should be added to the denominator for

figuring percent DCS at 22,500 ft because they were dropped from the study prior to being exposed at 22,500 ft. This adjustment should show a truer picture of population susceptibility at 22,500 ft. Thus, the 19 subjects exposed at 22, 500 ft should really be 21 subjects to include the two subjects who did not develop DCS at two higher altitudes (Webb and Pilmanis, 2005).
Synopsis: This study was sponsored by NASA and designed to determine the highest altitude at which individuals became symptom free during multiple exposures at the same or successively lower altitudes to determine an index of their susceptibility.

Bubble Threshold Study -- Bubble Threshold

The Bubble Threshold Study was initiated to investigate parameters for use in designing a pressure suit which would avoid the risk (as perceived by NASA) of high bubble grades during Extravehicular Activity (EVA). Activity was performed by the subjects to emulate the estimated levels of activity during EVA and the pressures varied to determine thresholds for any and severe (Grade 3+) VGE. The gas mixture was chosen to avoid 100% oxygen which complicates fire safety measures.
Synopsis: This NASA-sponsored study was designed to determine the threshold altitude at which subjects would develop venous gas emboli (bubbles) while breathing 50:50 N_2:O_2 and determined that VGE occurred as low as 10,250 ft and severe VGE as low as 14,400 ft.

Effect of Carbon Dioxide on Decompression Sickness -- CO2

The CO2 study initially involved 2, 3-h exposures to 25,000 ft with a 1-h prebreathe of either 100% oxygen or 97% oxygen and 3% carbon dioxide. After the first 71 exposures, it was obvious that the DCS incidence was insufficient (8-10%) to allow comparison of the prebreathe scenarios. The exposures were lengthened to 6 h and only 4 of 24 cases of DCS occurred after 3 h of exposure and the DCS incidence was 86% after 50 exposures. Only 2 subjects failed to develop DCS during their first 6-h exposure. The propensity for DCS to occur within 3 h during the 6-h exposure with an 86% incidence and only 9% during the 3-h exposures is baffling. Was the anticipation of 6 h of exposure too much for the subjects?
Synopsis: This study was sponsored by NASA and designed to determine if 3% CO_2 in the prebreathing gas would render the prebreathe more effective at preventing DCS. No difference between 100% oxygen and the CO_2-containing prebreathe mixture was shown.

Effect of Inflight Denitrogenation on Altitude DCS -- DNT

At the final altitude of 29,500 ft the subjects performed an exercise, rest, monitoring cycle designed to simulate the minimal exercise experienced by a pilot flying an aircraft and required about 110 Kcal·hr^{-1}. The exercise consisted of a 5-min period of rope pulling every 15 min throughout the exposure. The spring-loaded rope-pull device (MGI Mini Gym© Model 180; MGI Strength Fitness Systems™) was marked at a peak resistance of 75.6 N (17 lbs). When the timing light lit, the subject would pull the handgrip with both hands, from eye-height at arms' reach, to their lap, once each 5 sec, at a rate sufficient to cause the indicator to superimpose on the peak resistance mark. The subject held the handgrip in his lap until the timing light went off (about 2 s). When the timing light

went off, the subject returned the handgrip to eye-height at arms' reach to repeat the cycle. The rope-pulling exercise followed a 5-min period of rest seated in a chair and the rest was followed by a 5-min period of echo-imaging and joint flexion while reclined at the echo-imaging station.

The Kcal·hr^{-1} of exercise represents about 8-10% of $\dot{V}O_{2max}$. As such, it is the lowest of any of the "mild exercise" profiles included in development of ADRAC.

MFN 1991119 (Subject # 197) Profile K (15 min prebreathe at ground level followed by 2-h prebreathe at 18,000 ft) developed DCS during the staged-decompression at 105 min after arrival at 18,000 ft (joint pain; resolved during descent). This was the only incidence of DCS at any stage altitude during this study, although several cases of VGE were observed at stage altitudes.

Synopsis: The DNT study, sponsored by AFRL 6.2 funding, was designed to investigate the feasibility of inflight denitrogenation (DNT) in lieu of ground-level denitrogenation Results indicated that DNT was as effective at 16,000 ft as at ground level (Webb et al., 2000).

The effect of exercise-enhanced prebreathe on decompression sickness (DCS) risk at 25,000 ft -- EEP3

The multiple periods of exercise during prebreathe in this experiment were designed to take advantage of the benefit to multiple exercise bouts demonstrated by a large NASA study (Conkin et al. 2004). Where E = Dual-cycle ergometry at 75% of $\dot{V}O_{2peak}$; R = Ambulatory rest; and M = Mild dual-cycle ergometry at 30% of $\dot{V}O_{2peak}$, Profile A was 10E15R5E10R15M5R and Profile B was 10E15M5R (Webb et al., 2004).

Synopsis: The Exercise-Enhanced Prebreathe Study, supported by AFRL and USSOCOM demonstrated effectiveness of multiple exercise periods while breathing 100% oxygen prior to ascent on decompression sickness prevention for potential use during CV-22 operations.

Effect of Exercise on Altitude Decompression Sickness -- Effect of Exercise

An evolution from the Old ISO Study, this protocol used ambulatory rest with VGE monitoring during exposure to establish the highest altitude at which a subject would not develop DCS. The upper and first exposure altitude was set at 29,500 ft (to avoid the extra prebreathe requirement for inside observers at 30,000 ft vs. 29,500 ft). If the subject developed DCS during this first exposure, his (all male study) next exposure was at 27,500 ft, then 25,000 ft, then 22,500 ft until no DCS occurred. At the highest and earliest (in sequence) altitude where, at ambulatory rest with VGE monitoring, the subject did not develop DCS, the exercise exposures were commenced. A very thorough discussion of the methodology relating to exercise intensity and the stack-weight machine used during these exposures is contained in the Methods section of Pilmanis et al. (1999):

> For the purpose of determining the incidence of DCS at 29,500 ft, a composite of subject-exposures was used. If a subject did not develop DCS during the resting exposure at 29,500 and was not subsequently exposed to an exercising exposure, there is no way of knowing if they would have developed DCS during that subsequent exposure. Therefore, those 4 subject-exposures were dropped, leaving 14 subject-exposures at rest (29,500) with DCS, 10 more

who developed DCS during their first exercising exposure at 29,500 ft, and 17 who did not develop DCS for a total of 41 subjects exposed to 29,500 ft (mild exercise). This includes 24 subjects who developed DCS during the resting exposure at 29,500 ft and either did not participate further or were exposed later at lower altitudes. The DCS incidence for those 41 subjects was 58.5%.

Altitude of exposure Since the purpose of this study was to determine the relative importance of various modes of exercise in provoking altitude DCS, it was fundamental to determine the appropriate altitude at which each subject would accomplish the exercise. The appropriate altitude had to be low enough to prevent DCS at rest but high enough to provoke DCS with performance of at least one of the exercises. Two concepts were involved in determining the altitude at which the experiment should be conducted for each subject. The first is called the "altitude equivalent of exercise." The altitude equivalent of exercise is about 5000 ft (1524 m). The second concept is referred to in this paper as the "individual threshold altitude." This is defined as follows: The highest altitude in a series of stepwise decreasing altitudes at which the subject is symptom-free while at rest. The addition of exercise, or the altitude equivalent of the exercise, should, theoretically, induce DCS. The precision with which the threshold altitude is measured depends on the magnitude of the steps used in its determination. The threshold altitude in this study was determined to the nearest 2500 ft (762 m). This altitude interval was used because it had a reasonable chance to detect the reported 5000 ft altitude equivalent of exercise.

Resting exposures To determine the individual threshold altitude, the subject was first decompressed at 5,000 ft/min to the highest altitude which the protocol would allow, 29,500 ft. If he did not develop DCS, 29,500 ft was equal to or below his individual threshold altitude and 29,500 ft was, therefore, used throughout the rest of the experiment. If DCS did develop, he was exposed, at least a week later, to 27,500 ft. If DCS did not develop at this altitude, then 27,500 ft was used as his threshold altitude. If the subject did develop DCS at 27,500 ft, the cycle was repeated at progressively lower altitudes until DCS did not occur. Although it is possible that if subsequent resting exposures were accomplished at the "individual threshold altitude," DCS would have been observed, the fact that, at higher altitudes, the subject did develop DCS, supports an individual threshold altitude no higher than what was used here. Nine of the ten subjects whose individual threshold altitude was determined to be below 29,500 ft, developed DCS during at least one of the four, exercising exposures at the subjects' individual threshold altitude. The mean number of DCS cases per exercising exposure below 29,500 ft was 2.5, indicating that the concept of the individual threshold altitude was useful in obtaining results during the exercising exposures which could allow differential analysis.

Exercises during exposure Since the variable in this experiment was mode of exercise, the exercise intensity had to remain constant and low enough to prevent discomfort or significant oxygen debt which could confound clear diagnosis of DCS symptoms. On the other hand, the exercise intensity had to be sufficient to evoke DCS during performance of at least one mode of exercise. The task of determining the exercise levels was complicated by individual DCS

susceptibility. It is well known that some individuals develop DCS at relatively low altitude, while others are quite resistant to DCS (Gillies, 1965). Furthermore, a workload resulting in strenuous exercise for one person may represent light exercise to a more muscular or trained subject. Oxygen consumption measurements during ground-level studies were used to quantify the exercises to be used at altitude and to be sure the exercises were metabolically equivalent. The exercise intensity at which a subject worked at altitude depended on his strength, fitness, and size.

The stack weight machine shown in Pilmanis et al. (1999) was used to measure the subject's strength. This machine was specifically designed and constructed for this research. In The machine was set for arm measurements with the horizontal bar at arm height or for leg measurements with the horizontal bar at leg height. This bar was connected to a strain gauge and electric cord. During isometric arm exercise the subject pulled on this bar. The bar was locked in a stationary position. The amount of force was measured by the strain gauge and its output was displayed on a digital meter not shown. Isometric leg exercise was measured in the same way during a leg extension. The subjects performed maximum voluntary contraction (MVC) for 4 seconds. The MVC was repeated 3 times with an approximate 5-min rest period separating the trials. Because the leg exercise was an extension rather than a leg push, the arm pulling exercise allowed greater MVC in the large majority of subjects. The force exerted was recorded.

The stack weight machine was adjusted before each exposure for the size of the subject. A knob behind the back of the seat allowed for knee to buttocks distance adjustment, and the holes in the vertical oval plate could be used to adjust for arm or leg length.

The four modes of exercise were equated in a preliminary study (Fischer et al., 1993). For isometric arm exercise measurements, the horizontal bar was locked in place and the amount of force exerted by the subject was indicated on the meter connected to the strain gauge visible to the subject. Each subject was instructed what number on the digital meter he should reach when straining. The number on the digital meter ranged in graded steps representing 20-35% of his MVC in order to maintain comfort and freedom from oxygen debt. He maintained that force for 4 seconds, then rested for one second. This cycle was repeated for 4 minutes, with a 10 second rest at 2 minutes into the exercise period. During the exercise and for 4 minutes before and after the exercise (while the subject sat quietly) oxygen consumption was measured with the SensorMedics 2900Z. For dynamic arm exercise the subject pulled on the horizontal bar which was movable and connected to the weights by ropes and pulleys as shown in (Pilmanis et al., 1999). The weight load was set in graded steps from 8-20% of the MVC. Note that this MVC was smaller than the 20-35% MVC used for isometric exercise for reasons discussed in the introduction. The subject was monitored for oxygen consumption as before. He performed 20 cycles per minute for 4 minutes with a 10 second rest after 2 minutes. The third and fourth exercises, isometric and dynamic leg exercises, were performed like the arm

exercises, except that the horizontal bar was in the leg position (Pilmanis et al., 1999) to allow a leg extension exercise.

For each subject, four plots of oxygen consumption versus workload were constructed. Figure 3 shows an example of these plots for one subject, showing each of the four types of exercise, performed at a work load established for that subject based on his MVC results. A horizontal line was drawn across the plots to select an oxygen consumption common to all four exercises. In this way, it was possible to find a work load for each exercise which would generate equivalent rates of oxygen consumption. The exercise workload resulting in approximately 340 ml/min would allow equilibration of oxygen consumption between the four exercises. The work load for each exercise which produced the equivalent oxygen consumption was used during the altitude exposures.

In order to assess the subject's physical fitness and determine the metabolic cost of exercise to be performed during exposure, the Bruce treadmill (graded exercise) test was performed by each subject (Bruce et al., 1973; Pilmanis et al., 1999). As the subject exercised on the treadmill, monitoring of the oxygen consumption was accomplished with a SensorMedics 2900Z Metabolic Measurement Cart (Wiegman et al., 1993; Pilmanis et al., 1999). From the VO2max obtained during the Bruce test and the oxygen consumption measurements obtained during each of the exercises, a percentage of VO2max required by each exercise could be calculated.

The mean oxygen consumption of the subjects for all four exercises was 370 ml/min (12-min average; Pilmanis et al., 1999), which was 9.8% of the subject's mean VO2max. The 12-min average included resting times of 4 min before and after the 4-min exercise period.

Synopsis: This study was sponsored by NASA and showed that mode of exercise is not a factor in DCS risk with other conditions being standardized. Under our test conditions, there was no difference between dynamic and isometric exercise in eliciting DCS. Exercise during exposure to the symptom-free altitude for 4 hr produced a 40% incidence DCS (Pilmanis et al., 1999).

Decompression Sickness (DCS) Model Validation -- MV

The purpose of this study was to provide validation for a new altitude DCS risk assessment model developed at the Armstrong Laboratory. The "heavy" exercise consisted of cycle ergometry (Monarch 818E) at approximately 30% VO_{2peak} (2 kp, 60 rpm) for 3 of each 10 min. Subjects were ambulatory and monitored for VGE during the 7 min of rest between each exercise period (3/10 X 30% = 9%). The average % of VO_{2peak} during the ergometry was between 10 and 15 % after accounting for basal metabolism a very mild increase due to ambulation and VGE monitoring.

Synopsis: This study was sponsored AFRL 6.2 funding and provided validation of the Altitude DCS Risk Assessment Computer (ADRAC) model developed from Brooks data by predicting the risk of DCS under novel conditions validating the prediction with subject exposures.

The effect of breathing gas mixtures containing various inert gas levels on decompression sickness (DCS) risk -- N2O2

Due to nomenclature differences between the Technical Report TR and ASEM article (Pilmanis et al., 2005) in the DCS Database (Protocol Test #), the following cross-reference is shown with conditions during the 6, 240-min exposures:

Profile A = Protocol Test #1 = TR & ASEM article Test A
Zero prebreathe
60% nitrogen (226 mm Hg N_2) and 40% O_2 breathing mixture
18,000 ft
mild exercise

Profile B = Protocol Test #2 = TR & ASEM article Test B
Zero prebreathe
60% nitrogen (226 mm Hg N_2) and 40% O_2 breathing mixture
18,000 ft
heavy exercise

Profile C = Protocol Test #3 = TR & ASEM article Test C
Zero prebreathe
40% nitrogen (126 mm Hg N_2) and 60% O_2 as a breathing mixture
22,500 ft
mild exercise

Profile D = Protocol Test #4 = TR & ASEM article Test E
Zero prebreathe = Stage decompression at 16,000 ft
50% nitrogen (141 mm Hg N_2) and 50% O_2 as a breathing mixture
25,000 ft
mild exercise

Profile E = Protocol Test #5 = TR & ASEM article Test F
Zero prebreathe; Stage decompression at 16,000 ft
100% O_2 as a breathing mixture
25,000 ft
mild exercise

Profile F = Protocol Test #6 = TR & ASEM article Test D
90-min prebreathe w OBOGS (93% O_2, 2.8% N_2, 4.2% Ar)
OBOGS as a breathing mixture at altitude
25,000 ft
mild exercise

Synopsis: The N_2O_2 Study, funded by USSOCOM, supported use of inflight denitrogenation. Due to increased diffusion gradient of nitrogen even while breathing 60% nitrogen, no increase in decompression sickness risk was observed relative to use of 100% oxygen (Pilmanis et al., 2005).

The effect of isometric and isotonic exercise on altitude decompression sickness -- Old ISO Study

This study was an initial effort to determine the effect of exercise mode on altitude DCS. However, the results indicated that, at 25,000 ft, insufficient DCS would be evoked to allow a comparison of exercise effects. Since no subject completed all the planned exposures, all are listed as "withdrawn" meaning they did not finish the protocol. Also, the protocol called for three (3) exposures of each subject under each condition at 25,000 ft which would have taken well over a year of continuous participation for each subject; not likely. The requirement for 3 exposures was dropped to one (1) and a method to establish a sensitive altitude for DCS elicitation was initiated under the Effect of Exercise protocol.
Synopsis: The Old ISO study was initiated but then terminated due to design parameters which did not allow adequate data collection. It was revised and completed as the Effect of Exercise Study.

Pulmonary Tolerance to 100% Oxygen at 9.5 psia -- Oxygen Toxicity
Synopsis: NASA sponsored the Oxygen Toxicity study which determined that oxygen toxicity was not a factor during frequent exposures to 100% oxygen at 11,500 ft, a possible pressure suit environment allowing that pressure to be declared safe for EVA pressure suits (Webb et al., 1989).

Effect of Prebreathe with 100% Oxygen while Exercising on Incidence of Decompression Sickness (DCS) -- PE1

Synopsis: The Prebreathe with Exercise study. funded by NASA-Hq, determined that beginning prebreathe with a 10-min strenuous exercise reduced DCS risk relative to resting prebreathe of the same duration. It served as a basis for use on ISS from 2001-2006 (Webb et al., 1996).

Preoxygenation with exercise versus rest: Effect on incidence of decompression sickness (DCS) -- PE2
Synopsis: This NASA-sponsored research showed that 15-min of strenuous exercise at the beginning of a 90-min, 100% oxygen prebreathe was no better than 10-min at reducing DCS risk.

Post-Exposure Exercise and Risk of DCS -- Post-Exposure Exercise
The objective of this study was to determine the effect of exercise after altitude exposure (post-exposure exercise) on subsequent altitude decompression sickness (DCS) incidence. Existing USAF prohibition of exercise following altitude chamber training exposures and interest from operational personnel prompted our evaluation of post-exposure exercise as a DCS-inducing stressor. After a 1-h resting preoxygenation, 67 subjects were exposed to 30,000 ft for 2-h while performing mild, upper body exercise. The subjects were monitored for venous gas emboli (VGE) with an echo-imaging system and observed for signs and symptoms of DCS. Subjects without DCS (N=31) or with DCS which resolved during recompression (N=29) were randomly assigned to post-exposure rest (control, N=29) or moderate exercise (50% of peak oxygen uptake, dual-cycle ergometry; N=31) and both groups were monitored for delayed or recurring DCS. The altitude exposure resulted in 48.3% DCS in the 60 volunteers serving as test or control

subjects. Of 31 subjects assigned to the post-exposure exercise group, 15 had developed DCS which resolved during descent. No cases of DCS were observed or reported during or following post-exposure exercise. The results show that moderate exercise after exposure did not result in either delayed-onset or recurring DCS.
Synopsis: The Post-Exposure Exercise Study, sponsored by USSOCOM, indicated that decompression sickness is not a factor following exposures where exercise was performed after the exposure.

Altitude Effects on Photorefractive Keratectomy (PRK) Eyes -- PRK

This experiment was designed to cause hypoxia in the cornea of subjects and not to provoke or test DCS risk. No subjects developed DCS during the study. VGE data were not taken on the 35K exposures (N=80) since they only lasted a maximum of 30 min and other activities precluded observations.
Synopsis: The PRK study was funded by the USAF Surgeon General's Office and sought to determine if hypoxic conditions adversely affected vision of those who had PRK accomplished. No effects of DCS were observed.

Effect of repeat exposures on incidence of decompression sickness (DCS) -- Repeat

Calculation of DCS and VGE times necessitated development of queries which accounted for the descent, reascent, and ground residence times. The following fields (first line of columns in each query) allowed such corrections to provide total exposure time at FL250 prior to DCS or VGE incidence during C profile. Similar corrections were made for B profile.

0-30 min at FL250
Repemin atC1DCS: IIf([DCSanyMinutes]<31,[DCSanyMinutes],"")

1st Ground-Level Interval
Repemin atC2DCS: IIf([DCSanyMinutes]>30 And [DCSanyMinutes]<101,30,"")

31-60 min at FL250
Repemin atC3DCS: IIf([DCSanyMinutes]>100 And
[DCSanyMinutes]<131,[DCSanyMinutes]-70,"")

2nd Ground-Level Interval
Repemin atC4DCS: IIf([DCSanyMinutes]>130 And
[DCSanyMinutes]<201,[DCSanyMinutes]-60,"")

61-90 min at FL250
Repemin atC5DCS: IIf([DCSanyMinutes]>200 And
[DCSanyMinutes]<231,[DCSanyMinutes]-140,"")

3rd Ground-Level Interval
Repemin atC6DCS: IIf([DCSanyMinutes]>230 And
[DCSanyMinutes]<301,[DCSanyMinutes]-90,"")

91-120 min at FL250
Repemin atC7DCS: IIf([DCSanyMinutes]>300 And
[DCSanyMinutes]<331,[DCSanyMinutes]-210,"")
Synopsis: The Repeat Study was sponsored by USSOCOM and the results showed that incidence of decompression sickness was not increased during multiple exposures in one day relative to a continuous exposure of the same total duration.

Decompression sickness protection below 25,000 feet using 100% oxygen without prebreathe -- ZPB

Along with the protocol full titles which are commonly shortened for day-to-day use as shown above, the Study Design Table has fields to indicate the protocol number of record for both the Brooks Institutional Review Board (IRB, formerly the Advisory Committee for Human Experimentation, ACHE) and the USAF Surgeon General's Research Oversight Committee (HQ USAF/SGXC). Other fields include funding source (Sponsor-Contract), dates of first (Date Started) and last exposure (Date Completed) under each protocol, exposure parameters and activity during prebreathe, altitude, and postbreathe. The following activity descriptions, as abbreviated in the database Study Design Table, provide sufficient detail for documentation in reports. Each activity was either performed as described below or the exposure was terminated and listed as 'Incomplete'.
Synopsis: This NASA-sponsored study finished determination of the sigmoid curve representing the relationship between altitude and DCS risk during 4-h, zero-prebreathe exposures. The 5% DCS threshold was approximately 19,500 ft and the 50% threshold was observed at 23,200 ft (Webb et al., 2003).

Investigator field

Since 1983, the following investigators have been listed on protocols where DCS and/or VGE were the primary data gathered (omits PRK and LASIK):

Jimmy D. Adams, PhD
Ulf I. Balldin, MD, PhD
Gene A. Dixon, MBA
Michele D. Fischer, MS
William T. Harvey, MD
Christine L. Heaps, MS
Christopher M. Hearon, PhD
Ronald C. Hill, PhD
Nandini Kannan, PhD
Kevin M. Krause, PhD
Robert W. Krutz, Jr. , PhD
Michael S. Laughrey, MD
Robert B. O'Connor, MS
Robert M. Olson, MD, PhD
Lambros Petropoulos, MS
Andrew A. Pilmanis, PhD
Marvin T. Ryles, MD

James L. Skinner, MD
Kenneth W. Smead, MD
Zahid M. Sulaiman, BS
James T. Webb, PhD

Several statisticians participated in the documentation of results.
Dan Bauer, B.S.
Joseph R. Fischer, Jr., M.S.
Nandini Kannan, Ph.D.
Caroline Oakley, M.S.

Prebreathe Activity field

Non-Ambulatory Rest

Only used when no walking or standing was performed.
Used during PE1-B&D; PE2-A,B,D,&E;

Ambulatory Rest

During the studies where no "exercise" was performed during the exposure, subjects sat in a chair most of the time, getting up and walking to an echo-imaging station, assumed a semi-supine position, performed joint articulations for echo-imaging and then walked back to the chair and resumed sitting.
Used during BSI-A, Effect of Exercise-A,F,K,P,&U, MV-E, Old-Iso-K,P&U, PRK-A&D, and ZPB-B&F.

ARGOX-A,B,&C all preceding and following Dual Cycle Ergometry, 10 min.

Non-Ambulatory Rest and Dual Cycle Ergometry, 10 min

Used during the Adynamia and ARGOX studies, 180 min (3 h) prior to commencement of prebreathe, subjects were adynamic (Non-Ambulatory; not walking or standing, i.e. no weight along the long bones of the lower body), resting on a gurney. After three hours of Non-Ambulatory rest, the subject donned an oxygen mask (Intertechnique) and began breathing 100% oxygen while performing dual-cycle ergometry for 10 min, then rested, supine, for 50 min as in the PE1 study during the Adynamia study. During the ARGOX study, Non-Ambulatory Rest was then done for up to 255 min.

Dual Cycle Ergometry, 10 min

A dual-cycle ergometer consisting of two Ergomedic 818Es from Monark® (Varberg, Sweden) operated upright in tandem, was used as the exercise equipment. In operating the dual-cycle ergometer, the subjects used all major muscle groups by simultaneously exercising both arms at 40 rpm and legs at 60 rpm. The Test exercises performed at the beginning of preoxygenation consisted of 10 min of upright dual-cycle ergometry beginning with 2 min of warm-up

ergometry. The remaining 8 min were performed at 75% of each subject's VO_{2peak}.

The research design involved determination of peak oxygen consumption for each subject to establish work loads and ergometer speeds that would produce 70-80% of peak oxygen consumption during the preoxygenation procedure. Subjects performed arm work equal to 30% of the leg work rate at each level of the submaximal exercise. The level of exertion and duration of the dual-cycle ergometry was designed to avoid exercise-induced fatigue prior to altitude exposure. Resting preoxygenation was accomplished in the supine position. Used during PE1-A and Adynamia-A&B.

Dual Cycle Ergometer, 15 min

This exercise during preoxygenation employed two ergometers, both operated at 50 rpm. The ergometers consisted of a Monark® Leg Ergometer Model 818E and a Monarch® 881 Rehab Trainer 881 arm ergometer from Monark® (Varberg, Sweden). The exercise began with a 2-min, legs-only warm up and the remaining 13 min of the dual-cycle ergometry (arms and legs) was at 75% of peak oxygen uptake ($\mathbf{V}O_{2peak}$). The resistance was maintained at the combined resistance of the ergometers necessary to match the subject's level based on the USAF Cycle Ergometry Test estimate of VO_{2peak}. This extended the period at 70-75% of $\mathbf{V}O_{2peak}$ from 8 min during the previous study (10-min exercise including a 2-min warm-up; Webb et al., 1996) to 13 minutes.

Used during PE2-C&F.

Dual Cycle Ergometer, 10+5+15 min

Subjects' VO_{2peak} was used to calculate individualized workload during the prebreathe exercise. The leg ergometry constituted 80% of the total, dual-cycle work load. The prebreathe exercise consisted of a 2-min warm-up, followed by 8 min of dual-cycle ergometry at 75% VO_{2peak}, followed by 15-min of rest, followed by a 5 min of dual-cycle ergometry at 75% VO_{2peak}, followed by 10 min of rest, followed by 15 min of dual-cycle ergometry at 30% of $VO_{2peak.}$ The remaining prebreathe consisted of walking into the chamber to prepare for decompression. Used during EEP-A.

Dual Cycle Ergometer, 10+15 min

Subjects' VO_{2peak} was used to calculate individualized workload during the prebreathe exercise. The leg ergometry constituted 80% of the total, dual-cycle work load. The prebreathe exercise consisted of a 2-min leg-only, ergometry warm-up followed by 8 min of dual-cycle ergometry at 75% VO_{2peak}, followed immediately by 15-min of dual-cycle ergometry at 30%VO_{2peak}. The remaining prebreathe consisted of walking into the chamber to prepare for decompression. Used during EEP-B.

Stage Activity field

Non-Ambulatory Rest with VGE Monitoring

Non-Ambulatory Rest with VGE Monitoring during stage allowed no standing or walking, hence, Non-Ambulatory. Subjects sat in a reclined chair during the entire stage, their only activity besides rest being self-application of Doppler or echo-imaging probe gel and sequential articulation of each arm and leg joint during VGE monitoring.
Used only during ARGOX-B&C.

Ambulatory Rest with VGE Monitoring

Subjects sat in a chair for approximately 11-12 min then walked about 5-8 steps each way to get to and from their chair and the echo-imaging station. At the echo-imaging station, subjects would recline to allow VGE monitoring while articulating each joint of both arms and legs in sequence.
Used during DNT-D,E,F,G,H,I,&K and N2O2-D&E

Exposure Activity field

Non-Ambulatory Rest

Only used when no echo-imaging, walking, or standing is performed. Non-Ambulatory Rest involved so little movement as to be very near the level of Basal Metabolism. Used only during studies where avoidance of DCS was of primary concern during 30-min exposures.
Used during PRK exposures (no DCS).

Non-Ambulatory Rest with VGE Monitoring

The only activity besides seated rest was self-application of Doppler or echo-imaging probe gel and sequential articulation of each arm and leg joint during VGE monitoring every 10 min (varied slightly, occasional omissions). As with Non-Ambulatory Rest, this activity involved little movement and was near the level of Basal Metabolism.
Used during 35K-A & C, 40K, & Ascent Rate

Ambulatory Rest with VGE Monitoring

Subjects sat in a chair during most the exposure, walking only to get to and from the chair and the echo-imaging station. At the echo-imaging station, subjects would recline to allow VGE monitoring while articulating each joint of both arms and legs in sequence; 15 or 16-min cycles.
Used during BSI-A, Effect of Exercise-A,F,K,P,&U, MV-E, Old-Iso-K,P&U, PRK-A&D, and ZPB-B&F.

Ambulatory EVA Exercises

Extravehicular Activity (EVA) workload simulations, Ambulatory EVA Exercises, have been used during numerous studies (Dixon et al, 1986; Webb et al., 1996; Webb et al., 1998). They consist of three upper-body exercises and echo-imaging for venous gas emboli (VGE), 4 min each, lasting a total of 16 min per rotation and are performed throughout the exposure with or without 4-min breaks each hour. The exercise stations and VGE monitoring station are located against or on the walls surrounding a chamber space less than 3 X 4 m, requiring the subject to stand up and walk between stations. The metabolic energy required by the combined exercises was analyzed by Inderbitzen and DeCarlis (1986) at an average increase over resting (Metabolic Cost) of 67.8 kcal/h for males and 59.6 kcal/h for females.

- Station (1) Using a Monark 881 arm ergometer mounted about 1 m above the chamber floor, the subject cranks at 24 rpm with 20-Watt resistance as read on the 50 rpm ergometer scale, switching hands each 2 pedal revolutions (every 5 sec). When corrected for operating at 24 rpm while setting resistance on a 50-rpm scale [50/24], the 20 Watts equates to the 9.4 Watts used in earlier experiments[2] which employed a flywheel that traveled 6 m per pedal revolution [9.4W X 50rpm/24rpm = 19.6W];
- Station (2) Torque Wrench[3] (25 ft-lbs with an 18" torque wrench or 17 ft-lbs with a 15" torque wrench for 5 sec each position). The subject applies force with a torque wrench to bolt-like projections mounted on a wall for 5 sec in each position (push/pull/up/ down/left/right), alternately with each arm. The torque wrench used to attain the 25 ft-lbs was 44 cm from the center of the socket to the end of the wrench. A 26 cm torque wrench was used beginning in 1999 and the torque was adjusted to 17 ft-lbs to account for the shorter lever arm. At the center of each torque wrench grip, the force required to 'click' the torque wrench was 17 lbs for the 44 cm and 36 cm wrenches when set at the 25 ft-lb and 17 ft-lb settings, respectively.
- Station (3) Rope Pull[4] using wall-mounted pulley (Preston 805 rope pull; 17 lb resistance during pull from arms length to hip; one pull each 5 sec;

[2] Before 1999, a Monark 868 cycle ergometer was used in lieu of the current Monark 881. The 868 was mounted so the axel was about 4 ft high and was used with a hand-grip in place of a pedal. It was set to operate at 0.4 kp (4 Newtons) resistance with the subject cranking at 24 rpm, taking 5 sec to complete 2 pedal revolutions, alternating arms each two revolutions. The flywheel traveled 6 m per pedal revolution yielding the following workload:

0.4kp X 6 m/rev X 24 rev/min X 0.1635 Watts per kp-m/min = 9.4 Watts

[3] The torque wrench used to attain the 25 ft-lbs was 44 cm from the center of the socket to the end of the wrench. A 26 cm torque wrench was used beginning in 1999 and the torque was adjusted to 17 ft-lbs to account for the shorter lever arm. At the center of each torque wrench grip, the force required to 'click' the torque wrench was 17 lbs for the 44 cm and 36 cm wrenches when set at the 25 ft-lb and 17 ft-lb settings, respectively. At a second station, the subject applies force with a torque wrench, set at 25 ft-lbs, to bolt-like projections mounted on a wall for 5 sec in each position (push/pull/up/down/left/right), alternately with each arm.

[4] (4 of the 5 weights). [The spring-loaded rope-pull device (MGI Mini Gym© Model 180; MGI Strength

alternating hands); the subject pulls from arms reach at head level to their hip once each five sec, alternating left, right, then both arms.

- Echo-imaging to include joint articulation.
- Walking between exercise and VGE monitoring stations

[PE1 & 2; EEP, Post-Exposure Exercise, ZPB (all but B&F), 100% Suit Study, 9.5 psia Oxygen Toxicity Study]

Non-Ambulatory EVA Exercises

Same as Ambulatory EVA Exercises, except the subjects were reclined throughout the exposure so that the subject's legs did not support their body and no walking was performed. The torque wrench was mounted between the subjects legs, the arm ergometer was moved close enough for easy reach, and the rope pull was routed through pulleys to allow use while reclined. The activity cycle was 16 min. [Adynamia & ARGOX]

Cycle Ergomety at 30% VO2peak

Subjects rode a Monark 818E leg ergometer at 60 rpm for 4 of each 10 min. The remaining time was rest or echo-imaging, walking between exercise/monitoring stations and sitting in a chair. This should be considered moderate exercise since it was performed only 30% or less of the time and the resistance was reduced at the request of many of the subjects. [Model Validation-B,C,D]

Cycle Ergometry for 35K study

Subjects rode a Monark 818E leg ergometer at 60 rpm, 2.0 Kp for 3 of each 10 min. The remaining time was rest or echo-imaging, walking between exercise/monitoring stations and sitting in a chair. Although strenuous for the 3-min period, this should be considered moderate exercise since it was performed only 30% of the time (Metabolic Cost) [35K-B and 35K-D].

Dual-Cycle Ergometry at 50% VO2peak

(((3,000 ml/min X 50% - 300 ml/min)/2 ml/kp-m)/(6 m/pedal revolution X 60 rpm)

The formula for determining the kp on a Monark 818E leg ergometer required to produce 50% of VO2peak oxygen consumption is dependent on the VO2peak (l/min) of the individual, the meters of travel a point on the flywheel perimeter moves per ergometer pedal revolution (6 m/pedal revolution on the 818E; 2.33 m/pedal revolution on the 881E), and the number of revolutions per min (60 rpm) at which the ergometer is pedaled. A constant of 2 ml oxygen consumed per kilopond-meter (kp-m; kg-m) and correction for resting oxygen consumption (-300 ml/min) are included; e.g. an individual with a VO2peak of 3,000 ml/min (3.0 l/min), would work at 1.7 kp:

Fitness Systems™) was inadvertently set to 17 kg of resistance instead of 17 pounds of resistance for a period of at least 3 years between 1990 and 1995.] The pulley system (Preston 805 rope pull) replaced the Mini Gym apparatus in 1995 because the Mini Gym was beginning to produce variable resistance.

The exercise was performed during 8 min of each 16-min period and consisted of 60 rpm dual-cycle ergometry at 50% of $\dot{V}O_{2peak}$. The dual-cycle ergometer consisted of a Monarch® 818 leg ergometer (Varberg, Sweden) and a Monarch® 881 Rehab Trainer (Varberg, Sweden) mounted so the subject could sit upright pedaling the 818 leg ergometer while reaching forward to operate the 881 arm ergometer. To determine the appropriate resistance settings and target heart rate during the post-exposure moderate exercise periods, subjects were tested to $\dot{V}O_{2peak}$ (mean R value > 1.1) with dual-cycle ergometry. Since the exercise was performed during only half of the exposure period, the average $\dot{V}O_2$ [N_2O_2-B]

Rope Pull Exercise

- Rope Pull[5] using wall-mounted pulley (Preston 805 rope pull; 17 lb resistance during pull from arms length to hip; one pull each 5 sec; alternating hands) for 5 min each 15-min cycle of activity; the subject pulls from arms reach at head level to their hip once each five sec, alternating left, right, then both arms. The exercise, when performed without other two exercises in the "EVA" exercise triad, is estimated to use approximately 100 kcal/hour (Metabolic Cost) and should be considered light exercise. [DNT Study]
- Echo-imaging to include joint articulation.
- Walking between exercise and VGE monitoring stations

BSI Exercises

Every 15 min, the subjects perform 5, chair-height deep knee bends and then raise a 5-pound weight to arm's reach above their head 5 times with each arm. The subjects walk to and from the chair and the echo-imaging station where they recline and are monitored for VGE while performing mild joint articulation for about 4 min. During any remaining time each 15 min, the subjects remain seated at rest. Metabolic Cost unknown.

Effect of Exercise Study Exercises

Since the variable in this experiment was mode of exercise, the exercise intensity had to remain constant and low enough to prevent discomfort or significant oxygen debt which could confound clear diagnosis of DCS symptoms. On the other hand, the exercise intensity had to be sufficient to evoke DCS during performance of at least one mode of exercise. The task of determining the exercise levels was complicated by individual DCS susceptibility. It is well known that some individuals develop DCS at relatively low altitude, while others are quite resistant to DCS. Furthermore, a workload resulting in strenuous

[5] (4 of the 5 weights). [The rope pull was inadvertently set to 17 kg of resistance instead of 17 pounds of resistance for a period of at least 3 years between 1990 and 1995.] The pully system (Preston 805 rope pull) replaced the MiniGym apparatus in 1995 because the MiniGym was beginning to produce variable resistance.

exercise for one person may represent light exercise to a more muscular or trained subject. Oxygen consumption measurements during ground-level studies were used to quantify the exercises to be used at altitude and to be sure the exercises were metabolically equivalent. The exercise intensity at which a subject worked at altitude depended on his strength, fitness, and size.

The stack weight machine (see Pilmanis et al., 1999) was used to measure the subject's strength. This machine was specifically designed and constructed for this research. The machine was set for arm measurements with the horizontal bar at arm height. The machine was set for leg measurements with the horizontal bar at leg height. This bar was connected to a strain gauge and electric cord. During isometric arm exercise the subject pulled on this bar. The bar was locked in a stationary position. The amount of force was measured by the strain gauge and its output was displayed on a digital meter not shown. Isometric leg exercise was measured in the same way during a leg extension. The subjects performed maximum voluntary contraction (MVC) for 4 seconds. The MVC was repeated 3 times with an approximate 5-min rest period separating the trials. Because the leg exercise was an extension rather than a leg push, the arm pulling exercise allowed greater MVC in the large majority of subjects. The force exerted was recorded as $\dot{V}O_2$ during exposure (see Pilmanis et al., 1999) averaged 4.3 ml/kg/min during a 12-min average of whole-body $\dot{V}O_2$ including 8 min of rest.

The stack weight machine was adjusted before each exposure for the size of the subject. A knob behind the back of the seat allowed for knee to buttocks distance adjustment, and the holes in the vertical oval plate could be used to adjust for arm or leg length.

The four modes of exercise were equated in a preliminary study (see Fischer et al. 1993). For isometric arm exercise measurements, the horizontal bar was locked in place and the amount of force exerted by the subject was indicated on the meter connected to the strain gauge visible to the subject. Each subject was instructed what number on the digital meter he should reach when straining. The number on the digital meter ranged in graded steps representing 20-35% of his MVC in order to maintain comfort and freedom from oxygen debt. He maintained that force for 4 seconds, then rested for one second. This cycle was repeated for 4 minutes, with a 10 second rest at 2 minutes into the exercise period. During the exercise and for 4 minutes before and after the exercise (while the subject sat quietly) oxygen consumption was measured with the SensorMedics 2900Z.

For dynamic arm exercise the subject pulled on the horizontal bar which was movable and connected to the weights by ropes and pulleys. The weight load was set in graded steps from 8-20% of the MVC. Note that this MVC was smaller than the 20-35% MVC used for isometric exercise for reasons discussed in the introduction. The subject was monitored for oxygen consumption as before. He performed 20 cycles per minute for 4 minutes with a 10 second rest after 2 minutes. The third and fourth exercises, isometric and dynamic leg exercises, were performed like the arm exercises, except that the horizontal bar was in the leg position to allow a leg extension exercise.

For each subject, four plots of oxygen consumption versus workload were constructed. Figure 3 in Pilmanis et al. (1999) shows an example of these plots for one subject, showing each of the four types of exercise, performed at a work load established for that subject based on his MVC results. A horizontal line was drawn across the plots to select an oxygen consumption common to all four exercises. In this way, it was possible to find a work load for each exercise which would generate equivalent rates of oxygen consumption. In Figure 3, the exercise workload resulting in approximately 340 ml/min would allow equilibration of oxygen consumption between the four exercises. The work load for each exercise which produced the equivalent oxygen consumption was used during the altitude exposures.

In order to assess the subject's physical fitness and determine the metabolic cost of exercise to be performed during exposure, the Bruce treadmill (graded exercise) test was performed by each subject. As the subject exercised on the treadmill, monitoring of the oxygen consumption was accomplished with a SensorMedics™ 2900Z Metabolic Measurement Cart. From the $\dot{V}O_{2max}$ obtained during the Bruce test and the oxygen consumption measurements obtained during each of the exercises, a percentage of VO2max required by each exercise could be calculated.

The mean oxygen consumption of the subjects for all four exercises was 370 ml/min (12-min average), which was 9.8% of the subject's mean $\dot{V}O_{2max}$. The 12-min average included resting times of 4 min before and after the 4-min exercise period.

Exercising exposures After preoxygenation, the subjects were decompressed at 5,000 ft/min to their individual threshold altitude, as shown in **Fig 3**, and remained decompressed for 4 h. On separate, randomized flights, each subject did one of the 4 types of exercises every 20 min. The 20 min cycle was divided into five parts: 5 min of rest; 5 min of ultrasonic monitoring; 5 min of rest; 1 min to prepare for exercise; and 4 min of exercise. The subject walked across the chamber (1-10 ft) to be in position for the next activity. To provide relief from boredom and more closely emulate operational distractions, action-oriented movies were shown to the subjects during the hypobaric exposures. Search of the USAFSAM DCS Database indicated that, in an earlier study, all endpoint DCS symptoms were experienced during the first 4 h of 8-h exposures to 30,000 ft following a 1-h preoxygenation (n = 30). The 4-h exposure period used in the present effort was, therefore, considered adequate to detect the vast majority of DCS symptoms that would occur.

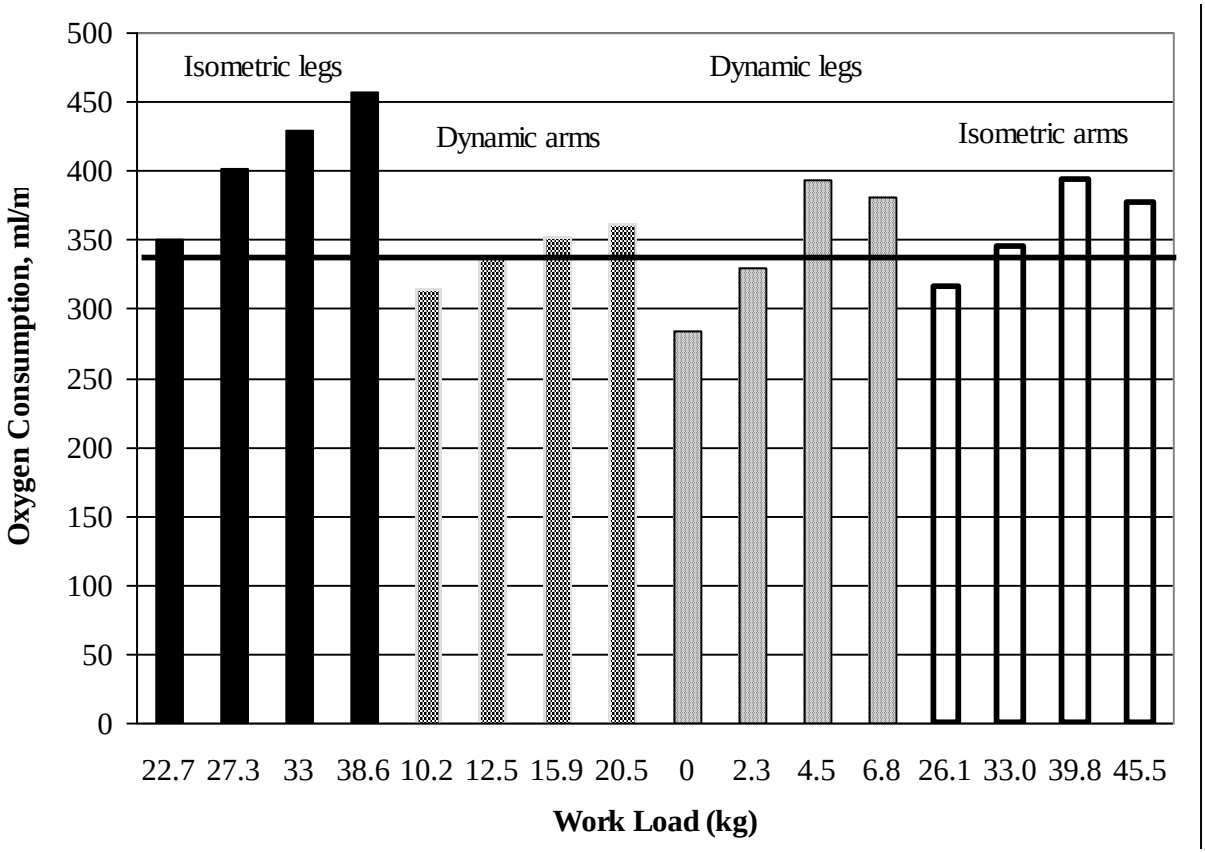

Fig 3. Work load versus oxygen consumption, Pilmanis et al. (1999)

Since the mean oxygen consumption of 9.8% of the subject's mean VO2max was determined by taking 12-min averages with 4 min of exercise bracketed by 4-min periods of rest, an adjustment had to be made to account for the other 8 min. Since the stack weight machine and subjects for that experiment are no longer available at this writing, an estimate of their average level of activity (metabolic cost) would have to be made without repeating the ground-level tests. The 20-minute mean Metabolic Cost is shown in Table 1.

Exposure Activity Level field

The Exposure Activity Level field is a numeric field which represents an average of the metabolic cost of activity above that of seated rest in l/min of oxygen consumed over the period of each activity cycle lasting 10-20 min. Metabolic cost of these activities was investigated (Webb et al., 2010) and mean metabolic cost (Table 2) recorded in the DCS Database.

Quantification of the level of activity required by the various activities while exposed was not determined with sufficient detail to allow peer-reviewed publication of the results. This was rectified when a study was completed in 2009 (Webb et al., 2010) that determined the minute-by-minutes metabolic rate with a COSMED K4b2 metabolic measurement system. Although that system is a breath-by-breath system, it allowed averaging by 30-sec which allowed comparison of mean metabolic rates and the highest 1-min Metabolic Rate,

ml/kg/min shown in Table 2. The relationship between average metabolic cost during a sequence of activity lasting from 10-20 min was poorly related to DCS risk observed during the four profiles. However, the highest 1-min of activity during any activity sequence was found to have a correlation of 0.9 with DCS risk at 29,500 ft to 30,000 ft after 1 h of prebreathe. The profile exposures at those altitudes lasted 4 h and the DCS incidence varied from 38 to 86%.

Table 2. Levels of Exposure Activity

ADRAC Activities, N	Mean Metabolic Cost, Kcal/h[12]	Highest 1-min Oxygen Consumption, ml/kg/min[12]
Rest [127][4,5]	73-78	5.2-7.6
Mild [716][6-9]	112	7.6-11.5
Heavy [60][10]	253	27.2
Database Activities		
Non-Ambulatory Rest [153[1,4]]	73	5.2
Ambulatory Rest [207[2,5]]	78	7.6
Ambulatory Stacked Weights [172[2,6]]	100	Not available
Rope Pull [280[2,7]]	110	8.8
Non-Ambulatory EVA [177[2,8]]	123	10.5
Ambulatory EVA [1378[1,2,9]]	162	11.5
Knee Bends & Dumbbell Lifts [318][2,11]	97	10.4
Cycle Ergometry [152[1,10]]	253	27.2

Note: The [N] listed is the number of subject-exposures in the database which used the activity listed. See Webb et al. (2010) for the data on metabolic cost and rate as shown in the Metabolic Cost/Rate columns.

[1] Exposures at 35,000 ft or 40,000 ft
[2] Exposures from 9,000 to 30,000 ft
[3] Equivalent to ADRAC, Heavy
[4] Seated rest; Echo-Imaging with joint movements
[5] Seated rest plus walking to a gurney for Echo-Imaging with joint movements. See Webb et al. (2005)
[6] Effect of Exercise extrapolation of total metabolic cost of activity. See Pilmanis et al. (1999). Highest 1-min Metabolic Rate not determined due to exercise equipment not available.
[7] Rope Pull exercise. See Webb et al. (2000)
[8] See Balldin et al. (2002)
[9] See Webb et al. (1989, 1993, 1998, 2002, 2003, 2005)
[10] See Webb et al. (2001)
[11] See Webb et al. (2005)
[12] Mean of Metabolic cost/rate. See Webb et al. (2010)

The retrospective study of oxygen consumption during exposure activity identified a strong positive correlation between DCS incidence and the highest one-min $\dot{V}O_2$ while decompressed. These quantified results expand the findings

in many previous reports where data on measured $\dot{V}O_2$ was not reported but exercise was shown to produce more DCS than resting altitude exposure. The quantified relationship presented in that paper (Webb et al., 2010) could improve efforts to predict the risk of DCS during planned altitude exposures using the ADRAC model (see Appendix 5) or other altitude DCS models. This improvement in accuracy could be expanded further with additional research at other altitudes and prebreathe times. It could allow consideration to modify peak level of activity while decompressed as a means of greatly reducing DCS risk.

Expansion of the understanding of $\dot{V}O_2$ on DCS risk could also explain differences between operational reports of DCS incidence and incidence during research studies of altitude DCS. In particular, the low incidence of DCS reported by aircrew who have low activity while decompressed, e.g. pilots, versus the high level of DCS observed during experimental exposures involving much higher levels of activity. These findings may also relate to DCS incidence following hyperbaric exposures with variable activity following decompression to normobaric conditions.

Postexposure Activity field

Dual Cycle Ergometry at 50% VO2peak

The post-exposure exercise consisted of three, 15-min periods of 60 rpm dual-cycle ergometry at 50% of VO_{2peak}, beginning 5 min after recompression. The dual-cycle ergometer consisted of a Monarch® 818 leg ergometer (Varberg, Sweden) and a Monarch® 881 Rehab Trainer (Varberg, Sweden) mounted so the subject could sit upright pedaling the 818 leg ergometer while reaching forward to operate the 881 arm ergometer. To determine the appropriate resistance settings and target heart rate during the post-exposure moderate exercise periods, subjects were tested to VO_{2pea}k (mean R value > 1.1) with dual-cycle ergometry. The post-exposure exercise was accomplished while breathing room air and neither exercising nor resting subjects were restricted from normal activity, including walking and eating. The exercise periods were separated by 15 min of rest that included VGE monitoring as necessary to determine when VGE resolved at ground level. Resting subjects were also monitored for VGE to determine time of resolution. Due to equipment and personnel limitations, the resting subjects were monitored for post-exposure VGE 10 min earlier than the exercising subjects.

Ambulatory Rest with VGE Monitoring

Subjects sat in a chair during most of the postexposure period (usually postbreathing for two h with 100% oxygen unless stipulated otherwise), walking only to get to and from chair and echo-imaging station. At the echo-imaging station, subjects would recline to allow VGE monitoring while articulating each joint of both arms and legs in sequence. When VGE could no longer be detected, the remaining time of postbreathing was mostly spent seated.

Subject Table

This table contains information subject to the Privacy Act of 1974 and must be protected accordingly. Hence, any retrieval containing sensitive information from this table must be likewise protected. The sensitive fields are: Last Name, First Name, Race, Gender, and Date of Birth. With these fields deleted from a copy of the database, it becomes almost impossible to associate a given subject-exposure with a given subject or to relay privacy act information. Age of the subject at any given subject-exposure (MFN) may need to be addressed in a separate query if age is needed for an anonymous report.

Occasionally, a subject would manifest a reaction during an exposure which caused their removal from the subject pool by a Flight Surgeon or Medical Monitor. Although this was viewed as necessary to protect the subject from further risk of possible serious symptoms of DCS, it had the effect of slanting the results of any protocol in which the subject may have participated at a later date. Thus, if subject "A" was removed after developing neurologic DCS symptoms during an exposure provoking 50% DCS in all subjects participating, the lack of subject "A" in a later protocol exposure yielding 65% DCS would have the effect of lowering the result recorded in the database. This would yield a lower reported risk than may actually exist. While isolated cases would have little effect on outcome, there were a few periods between 1990 and 2004 when several subjects were removed.

Injury Table

Region field

”Anterior”; “Anterior and Posterior”; “Bilateral”; “Bilateral Anterior”; “Bilateral Anterior and Posterior”; “Bilateral Lateral”; “Bilateral Medial”; “Bilateral Posterior”; “Central”; “Left”; “Left Anterior”; “Left Lateral”; “Left Medial”; “Left Posterior”; “Posterior”; “Right”; “Right Anterior”; “Right Lateral”; “Right Medial”; “Right Posterior”

Location field

“Abdomen”; “Ankle”; “Back”; “Calf (lower leg)”; “Chest”; “Chest (Thorax)”; “Ear”; “Elbow”; “Entire Body”; “Extremities”; “Eye”; “Fingers”; “Foot”; “Forearm”; “Hand”; “Head”; “Hip”; “Knee”; “Multiple Sites”; “Neck”; “Nondescript”; “Pelvis”; “Shin (lower leg)”; “Shoulder”; “Sinus”; “Thigh (upper leg)”; “Toes”; “Tooth”; “Upper Arm”; “Whole Arm”; “Whole Leg”; “Wrist”

Flight Table

Man Flight Number field

This is an auto-number generated when a new subject-exposure is entered in the Flight table. It is unique to each subject-exposure and cross-referenced in all other tables except the Study Design Table and the Subject Table. The Flight Table is linked to the Study Design Table by the Short Title and Profile fields. The Flight Table is linked to the Subject Table by the Subject Number field.

Menstruation Day field

During the 1980s this field was designed to reflect the percentage of cycle completion. Unfortunately, there was inadequate standardization of definition of start day and the data were, therefore, unreliable and were removed. Fortunately, there were no protocol profiles affected wherein the DCS risk was greater than about 5% and included female subjects.

Smoking History field

Since all protocols in the 90s and beyond required subjects to be non-smokers for the preceeding 2 years, this field is largely useless unless a comparison of "Former Smoker" to "Never Smoked" was desired.

VO_{2max} field

The $\mathbf{V}O_{2max}$ entries were derived from the: US Air Force cycle ergometry fitness test estimate of $\mathbf{V}O_{2max}$; a Bruce Protocol Treadmill test; or a $\mathbf{V}O_{2peak}$ determined with a dual-cycle ergometer test to maximal oxygen consumption as described in the Guide to Altitude Decompression Sickness Research appendix "TESTING FOR AEROBIC CAPACITY."

VO_{2max} source

AF test = Air Force Fitness Test (cycle ergometry); Dual = Dual-Cycle Ergometry; Treadmill = Bruce Test on a Treadmill; the most recent test result was entered

Chamber Number

C-Chamber (C) was used for all but the PRK study which was done in E-Chamber (E).
C-Chamber is a rectangular steel structure known as a 20 man chamber which has been modified for research purposes. The interior of the chamber is 30 feet 8 inches in length, 8 feet wide, and 8 feet high. The main door opening is 6 feet 6 inches high by 3 feet wide. The compartments of C chamber may be evacuated to simulate any desired altitude between ground level and 50,000 feet using two Nash vacuum pumps or 100,000 feet using 5 Kinney vacuum pumps. These two systems are used independently with isolation valves. The chamber is structurally able to go to 100,000 feet. Altitude may be controlled either manually or automatically. The chamber can be kept at altitude for a period of at least one year.

E-Chamber has an internal volume of 5000 cubic feet with a main door opening of 7'10" and useable space as follows:

1. front area: 7'2" high x 9'10" wide x 25'5" long
2. rear area: 9'5" high x 11' wide x 16'8" long
3. mid area: 7' high x 5'4" wide x 9'7" long

The chamber may be evacuated to simulate any desired altitude between ground level and 100,000 feet. A simulated altitude of 100,000 feet can be reached in12 minutes at an average rate of climb of 8,300 feet per minute. The chamber can be controlled either manually or automatically. In addition to going to altitude, the chamber's temperature and humidity can be controlled via computer to meet the

specific needs of the study/protocol conducted. The temperature within the chamber may be reduced, at ground level conditions, from ambient temperature to –67 degrees Fahrenheit (-55 C). The temperature can also be raised, at ground level conditions, from ambient temperature to 150+ degrees Fahrenheit (65.6 C).
The chamber consists of a main portion and lock portion, each can be moved independently of one another. A very large door provides easy access into the chamber for large pieces of equipment. The door's proximity to an alley entrance makes loading and unloading equipment from outside fairly simple.

Bubble Detection Method field

"None"
"IAPM Doppler"
Precordial Doppler Ultrasound, Bidirectional Doppler Model 1053 from the Institute of Applied Physiology and Medicine, Sound Products Division, Seattle, WA and 2D Cardiac Ultrasonic Echo-Imaging, IREX System 3 echo-imaging system from IREX Medical Systems, Ramsey, NJ.
"HP SONOS 500"
Precordial Doppler Ultrasound and 2D Cardiac Ultrasonic Echo Imaging; Hewlett-Packard SONOS 500 Echo-Imaging System
"HP SONOS 1000"
Precordial Doppler Ultrasound and 2D Cardiac Ultrasonic Echo Imaging; Hewlett-Packard SONOS 1000 Echo-Imaging System

HISTORY OF ULTRASOUND/ECHO-IMAGING TECHNOLOGY USED TO OBTAIN VGE INFORMATION FOR INCORPORATION IN THIS DATABASE

Precordial Doppler Ultrasound

Bidirectional Doppler Model 1053 from Institute of Applied Physiology and Medicine, Sound Products Division, Seattle, WA

MFN 1983001-84152; 8Oct83-19Oct84
MFN 1985037-85191; 9Apr85-20Nov85*

2D Ultrasonic Echo Imaging

IREX System 3 from IREX Medical Systems**

Precordial Doppler Ultrasound and 2D Ultrasonic Echo Imaging

Hewlett Packard SONOS 500 Echo Imaging System

MFN 1984153-1985036; 22Oct84-27Mar85
MFN 1985192-1991113; 26Nov85-10Oct91*

Precordial Doppler Ultrasound and 2D Ultrasonic Echo Imaging

Hewlett Packard SONOS 1000 Echo Imaging System

MFN 1991114- ; 18Oct91-

Use of the SONOS 500 or the dual-probe, earlier system was mixed in 1984-1985. The MFNs and dates are for majority use by one system, not exclusive use during that period.

The dual-probe system did not have a unique bubble detection system code. Thus, code "02", the 2D Ultrasonic Echo Imaging IREX System 3 from IREX Medical Systems, is not specified in the database as it could have been.

FIRST MENTION OF VARIOUS METHODS USING DOPPLER ULTRASOUND

1. Detection of circulating gas emboli with Doppler; invasive:

Spencer MP and Campbell SD. Development of bubbles in venous and arterial blood during hyperbaric decompression. Bulletin of the Mason Clinic. 1968; 22:26-32 (March). No mention of "counting"

Spencer MP and Campbell SD. Bubbles in the blood during hyperbaric decompression. Intl. Union Physiol. Sci. 1968; VII:412. No mention of "counting"

Gillis MF, Peterson PL, Karagianes MT. In vivo detection of circulating gas emboli associated with decompression sickness using the Doppler flowmeter. Nature 1968: 217:965-7 (March 9, 1968).

Walder DN, Evans A, Hempleman HV. Ultrasonic monitoring of decompresson. Lancet. 1968; 1:897. (April 27, 1968).

2. Detection of circulating gas emboli with Doppler; non-invasive (transcutaneous):

Sutphen, JH. The Feasibility of Using Pulsed Ultrasound to Detect the Presence of in vivo Tissue Gas Bubbles. U.S. Naval Submarine Medical Center Report #508, Submarine Medical Research Laboratory, Research Work Unit MF011.99-9003.01. 25pp. (27 February 1968).

Gillis MF, Karagianes MT, Peterson PL. Bends: Detection of Circulating gas emboli with external sensor. Science 1978;161:579-580. (9 August 1968).

3. Detection of circulating gas emboli with Doppler; non-invasive (precordial):

Maroon JC, Edmonds-Seal J, Campbell RL. An ultrasonic method for detecting air embolism. J. Neurosurg. 1969; 31:196-201.

Spencer MP, Simmons N, Clarke HF. A precordial transcutaneous cardiac output and aeroembolism monitor. Fed. Proc. 1971; 30:703.

Spencer MP, Clarke HF. Precordial monitoring of pulmonary gas embolism and decompression bubbles. Aerosp. Med. 1972; 43:762-7.

Spencer MP, Johanson DC. Investigation of new principles for human decompression schedules using the Doppler ultrasonic blood bubble detector. TR ONR Contract N00014-73-C-0094. 1974;88pp.

Neuman TS, Harris MG, Linaweaver PG. Blood viscosity in man following decompression: Correlations with hematocrit and venous gas emboli. Aviat. Space Environ. Med. 1976;47:803-7.

4. Grading scale, 0-4

Spencer MP. Decompression limits for compressed air determined by ultrasonically detected blood bubbles. J. Appl. Physiol. 1976;40:229-35.

[*this article was published in February, 1976; the original manuscript was received on 3 February, 1975]*

Grade 0 = no bubble signals

Grade 1 = an occasional bubble signal with the great majority of cardiac cycles free of bubble signals

Grade 2 = many but less than half of the cardiac cycles contain bubble signals

Grade 3 = bubbles in most or all of the cardiac cycles but not obscuring the heart sounds

Grade 4 = numerous bubbles that obscure the heart sounds

Neuman TS, Hall DA, Linaweaver PG Jr. Gas phase separation during decompression in man: Ultrasound monitoring. Undersea Biomed. Res. 1976;3:121-30.

[*this article was published in June, 1976; the revised manuscript was received in March, 1976 (after the Spencer article was published; cited Spencer & Johanson, 1974); the original manuscript was received in December, 1975]*

Mask Number field

The mask number is the number of the mask used for that flight exposure. The mask and regulator used for all but two and part of another study exposures was the neck-seal respirator made by Intertechnique® (Plaisir Cedex, France). It provided a slight, 2 cm of water, positive pressure which reduced the opportunity for inboard leaks of nitrogen from ambient air. This respirator is also more comfortable than the standard aviator's mask.

On occasion, a more comfortable mask was used for prebreathe or postbreathe, but also provided adequate seal to prevent inboard flow of atmospheric nitrogen. Examples are the MBU-12/P, MBU-A, Other-B/P, and MBU-5/P masks; HGU-7/P, HGU-10/P, or HGU-55/P helmets, and the A-1D-2 or A-14 regulator.

For the PRK study profiles to 35,000 ft, an MBU-5/P mask, HGU-55P helmet, and A-14 regulator were used. The Farnborough study used the RAF P/Q mask with the helmet/regulator available in the UK. For some of the CO2 study exposures, especially profile C, an MBU-AOther-B/P mask, HGU/7 or 10/P helmet and A-1D-2 regulator were used.

Segment Table

Segments of the exposure day are consecutive, beginning with #1 which starts when the subject arrives for the exposure before any prebreathe. Each segment represents a change in altitude or a constant altitude. In most cases the ear and sinus check at 5,000 ft (632 mmHg) were deleted or not entered because it was a bounce decompression and no symptoms other than ear problems were ever observed. In those cases, the exposure was discontinued unless the subject could resolve the problem. However about 400 segments related to this check remain in the database.

Segment Type

"Ground Level Isobaric";"Flight Ascending";"Altitude Isobaric Stage";"Altitude Isobaric";"Flight Descending"

Reason for Termination

"Planned Completion";"Subject Request";"DCS";"Adverse Subject Response";"Equipment Failure";"Adverse I/O Response";"Other";"LVGE Observed";"LVGE Observed & DCS"

Symptom Table

Endpoints (test termination criteria) of the exposures were: 1) completion of the scheduled exposure; 2) development of any DCS signs or symptoms including respiratory symptoms, neurologic symptoms, paresthesia, and constant pain; 3) detection of LVGE; 4) subject request.

A complete description of each symptom is shown in the following fields.

Onset Time field

Clock time of the each reported symptom is recorded unless the subject reported that a symptom began earlier and that time would be recorded. If a symptom was delayed or recurred the next day or later, the symptom onset time was recorded as occurring at 11:59pm the day of the exposure to prevent difficulties in determining minutes to onset time in the queries. This was a rare occurrence and the large number of minutes, well beyond the exposure time, should alert any researcher to look more closely.

Description field

"Abnormal reflex";"Additional information in 'Comments'";"Blurred vision";"Cold sweat";"Cough";"Decreased mental status";"Dermatomal, see comments";"Dizziness";"Dyspnea (difficult or labored breathing)";"Ear pain";"Edema";"Erythema (red rash, not raised)";"Fatigue (inappropriate or sudden onset)";"Headache";"Hot and/or cold sensation";"Hyperesthesia (increased sensitivity to stimulation)";"Impaired coordination/gait";"Joint awareness, stiffness";"Joint pain";"Light headedness";"Loss of consciousness";"Muscle pain";"Muscle spasm";"Muscular weakness (motor loss)";"Nausea";"Numbness (sensory loss)";"Pain, not perceived in joint or muscle";"Pallor";"Pins & needles, tingling, prickling";"Pruritus (skin itch)";"Sinus

pain";"Skin mottling";"Substernal distress (Tightness in chest)";"Tooth pain";"Tremor, shakes";"Unresponsive";"Urticaria (itching weals or welts, elevated)";"Vertigo"

Note: The underlined symptoms are not DCS symptoms

Note: If a Pins & needles, tingling, prickling symptom exhibits a dermatomal distribution, the comments should contain more specific information including verification that the symptom was pins & needles, tingling, prickling.

Region field

Identical choices as *Region field* in Injury Table: ”Anterior”; “Anterior and Posterior”; “Bilateral”; “Bilateral Anterior”; “Bilateral Anterior and Posterior”; “Bilateral Lateral”; “Bilateral Medial”; “Bilateral Posterior”; “Central”; “Left”; “Left Anterior”; “Left Lateral”; “Left Medial”; “Left Posterior”; “Posterior”; “Right”; “Right Anterior”; “Right Lateral”; “Right Medial”; “Right Posterior”

Location field

Identical choices as *Location field* in Injury Table: “Abdomen”; “Ankle”; “Back”; “Calf (lower leg)”; “Chest”; “Chest (Thorax)”; “Ear”; “Elbow”; “Entire body”; “Extremities”; “Eye”; “Fingers”; “Foot”; “Forearm”; “Hand”; “Head”; “Hip”; “Knee”; “Multiple sites”; “Neck”; “Nondescript”; “Pelvis”; “Shin (lower leg)”; “Shoulder”; “Sinus”; “Thigh (upper leg)”; “Toes”; “Tooth”; “Upper Arm”; “Whole arm”; “Whole leg”; “Wrist”

Note: Extremities means arms and legs, both (unusual)

Temporal Sense

"Transient, with movement only";"Transient";"Constant"

There should be no

Treatment field

"120 min 100% O2 at sealevel pressure";"Hyperbaric, Table V";"Hyperbaric, Table VI";"Precautionary Hyperbaric, Table V";"Precautionary Hyperbaric, Table VI";"HBO for a different symptom";"None";"120 min GLO2 THEN Hyperbaric Therapy";"Other"

Treatment Results field

"";"Symptom(s) resolved before treatment";"Symptom(s) resolved with first treatment";"Symptom(s) resolved with multiple treatments";"Residual symptom(s) remain after treatment(s)"

Symptom Remarks field

Symptoms occasionally occur or reoccur after an exposure. If the symptom occurs for the first time after the exposure it is called a "delayed symptom" and so noted in this field and in the Flight Comments field of the Flight table. If a delayed symptom occurs and no other DCS symptom occurred during that exposure prior to its completion (Planned Completion entered in the Segment table for the Altitude Isobaric segment), then the Onset Time should be adjusted to match the end of the completed exposure time, e.g. 4 h after arrival at altitude for studies with a 4-h exposure to properly show the maximum duration of exposure that caused the symptom. Otherwise, delayed symptoms should be shown as occurring at the last minute of the exposure which

caused them, i.e. Segment Start Time for Flight Descending. Also, the actual time of occurrence of the delayed symptom should be entered in the Symptom Remarks field beginning with "Delayed symptom, " to allow extraction of standardized information on delayed symptoms. If the symptom occurred during the exposure, resolved at some point and then occurred again, it is called a "recurring symptom" and so noted in this field and in the Flight Comments field of the Flight table.

In searching for delayed or recurring symptoms, a query must use criteria of Delayed or Recurring in the Symptom Remarks or Flight Comments field.

Bubble Table

Validation Rules [<5] apply to bubble grades in all but the “Source Other” field which is filled with “99” to indicate Left Ventricular Gas Emboli (LVGE).

At intervals of 10-20 min (protocol test plan dependent), the subjects were monitored for venous gas emboli (VGE) using the available system as indicated in the Flight record. The monitoring periods lasted approximately one to two minutes each and included 5 recorded VGE scores. The “general” VGE score was taken with the subject at rest after positioning for monitoring specific to each protocol. A VGE score was then taken, in turn, as each limb was flexed and rotated twice. A 5-point VGE grading scale similar to the Spencer Scale (Spencer, 1976) was used. Each VGE score was an average during the monitoring period. This method is considered to be semi-quantitative, recognizing that a precise number of bubbles in a heart cycle is difficult/impossible to determine with the current technology, the number varies from cycle to cycle in a monitoring period, the same bubbles may be counted more than once, etc. The Grades were defined as follows:

Grade 0 = no bubble signals
Grade 1 = occasional bubble signals
Grade 2 = frequent bubble signals
Grade 3 = many bubble signals, but they do not obscure the heart sounds
Grade 4 = numerous bubble signals that obscure the heart sounds

These bubble grades were used consistently throughout the period of data collection, 1983 to 2005. Due to the divergence of the Spencer Scale and the scale used here regarding Grades 2 and 3, only incidence of any VGE or of Grade 4 VGE are considered effectively synonymous and used for reporting and quantification of VGE incidence.

APPENDIX A: REFERENCES
BASED ON INFORMATION FROM THE AIR FORCE RESEARCH LABORATORY ALTITUDE DECOMPRESSION SICKNESS RESEARCH DATABASE

Articles/abstracts based on multiple studies in *italics*.

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APPENDIX C: Example of Query Construction to Adjust Time of DCS Relative to the Planned Beginning of the Exposure Based on the Start Time of the Isobaric Stage

In the following example, ARGOX-B, the time between arrival at the stage altitude and planned arrival at the exposure altitude was 257 minutes. The Segment Start Time was, in the "" query, derived from the altitude isobaric stage segment type's segment start time.

StageDCSARGOXb: DateDiff("n",[firstofSegment Start Time],[MinofOnset Time])-257

tDetailedReport is created by qDetailedReportTable from two queries:

- qDetailedReportBasis which is based on
  - tFlight, tSubject, tStudy Design
- qVGEDCSminutes which is based on, in succession
  - tFlight, tSubject
  - qVGEminutes
    - qVGEanyTime
      - tFlight
      - tBubble
    - qVGEanyMinutes
      - qSegmentStart
        - tFlight
        - tSegment
      - qVGEanyTime
        - tFlight
        - tBubble
    - qVGEMinutesDNTstage
      - qStageVGEDNTd
        - qVGEanyTime
          - tFlight
          - tBubble
      - qSegmentStartStage
        - tFlight
        - tSegment
      - qVGEanyTime
        - tFlight
        - tBubble
      - qStageVGEDNTe
        - qVGEanyTime
          - tFlight
          - tBubble
      - qSegmentStartStage
        - tFlight
        - tSegment
      - qVGEanyTime

tFlight
tBubble
qStageVGEDNTf
qVGEanyTime
tFlight
tBubble
qSegmentStartStage
tFlight
tSegment
qVGEanyTime
tFlight
tBubble
qStageVGEDNTg
qVGEanyTime
tFlight
tBubble
qSegmentStartStage
tFlight
tSegment
qVGEanyTime
tFlight
tBubble
qStageVGEDNTh
qVGEanyTime
tFlight
tBubble
qSegmentStartStage
tFlight
tSegment
qVGEanyTime
tFlight
tBubble
qStageVGEDNTi
qVGEanyTime
tFlight
tBubble
qSegmentStartStage
tFlight
tSegment
qVGEanyTime
tFlight
tBubble
qStageVGEDNTj
qVGEanyTime
tFlight
tBubble

qSegmentStartStage
tFlight
tSegment
qVGEanyTime
tFlight
tBubble
qStageVGEDNTk
qVGEanyTime
tFlight
tBubble
qSegmentStartStage
tFlight
tSegment
qVGEanyTime
tFlight
tBubble
qVGEMinutesARGOXandN2O2stage
qVGEanyTime
qStageVGEARGOXb
qStageVGEARGOXc
qStageVGEn2o2d
qStageVGEn2o2e
qVGE4minutes
qVGE4anyTime
qVGE4anyMinutes
qVGE4MinutesDNTstage
qVGE4MinutesARGOXandN2O2stage
qDCSminutes
qDCSanyTime
tFlight
tSymptoms
qDCSanyMinutes
qDCSanyTime
qSegmentStart
qDCSMinutesDNTstage
qStageDCSDNTd
qDCSanyTime
tFlight
tBubble
qSegmentStartStage
tFlight
tSegment
qDCSanyTime
tFlight
tBubble
qStageDCSDNTe

qDCSanyTime
tFlight
tBubble
qSegmentStartStage
tFlight
tSegment
qDCSanyTime
tFlight
tBubble
qStageDCSDNTf
qDCSanyTime
tFlight
tBubble
qSegmentStartStage
tFlight
tSegment
qDCSanyTime
tFlight
tBubble
qStageDCSDNTg
qDCSanyTime
tFlight
tBubble
qSegmentStartStage
tFlight
tSegment
qDCSanyTime
tFlight
tBubble
qStageDCSDNTh
qDCSanyTime
tFlight
tBubble
qSegmentStartStage
tFlight
tSegment
qDCSanyTime
tFlight
tBubble
qStageDCSDNTi
qDCSanyTime
tFlight
tBubble
qSegmentStartStage
tFlight
tSegment

qDCSanyTime
tFlight
tBubble
qStageDCSDNTj
qDCSanyTime
tFlight
tBubble
qSegmentStartStage
tFlight
tSegment
qDCSanyTime
tFlight
tBubble
qStageDCSDNTk
qDCSanyTime
tFlight
tBubble
qSegmentStartStage
tFlight
tSegment
qDCSanyTime
tFlight
tBubble
qDCSMinutesARGOXandN2O2stage
qDCSanyTime
tFlight
tBubble
qStageDCSARGOXb
qStageDCSARGOXc
qStageDCSn2o2d
qStageDCSn2o2e

APPENDIX D: BASIS FOR DEVELOPMENT OF THE ALTITUDE DCS RISK ASSESSMENT COMPUTER (ADRAC) MODEL

Table D1. ADRAC Study Titles Profiles, and Numbers of Subjects

Study Title-Profiles	Subject N
100% Suit-A	10
100% Suit-B	10
100% Suit-C	10
100% Suit-D	10
100% Suit-E	10
100% Suit-F	10
35K-A	37
35K-B	30
35K-C	36
35K-D	31
BSI-A	15
BSI-B	37
CO2-A	38
CO2-C	25
DNT-A	39
DNT-B	18
DNT-C	32
Effect of Exercise-A	46
MV-A	31
MV-B	31
MV-C	30
MV-D	30
MV-E	31
Oxygen Toxicity-A&B	42
PE1-B	28
PE2-A	32
PE2-B	32
PE2-D	31
PE2-E	32
Post-Exposure Exercise-A	19
Post-Exposure Exercise-B	19
Post-Exposure Exercise-C	5
Repeat-A	35
ZPB-A	20
ZPB-B	20
ZPB-C	20
ZPB-D	10
ZPB-E	20
ZPB-F	22
ZPB-G	20
ZPB-H	9

This table shows the 41 altitude decompression research protocol profiles used in development of ADRAC Version 5. The total N of completed exposures was 1012. The 1015 reported in the Model Validation paper (Pilmanis et al., 2004; list above) included 3

exposures which were subsequently removed from the calculations because they represented incomplete exposures, ones that did not terminate with a valid endpoint iaw the protocol.

APPENDIX E: ACRONYMS

AFRL	Air Force Research Laboratory
AFSOC	Air Force Special Operations Command
AGE	Arterial Gas Emboli
DCS	Decompression Sickness
EKG/ECG	Electrokardiograph (German), electrocardiograph (English)
EVA	Extravehicular Activity
ICD	Informed Consent Document
IRB	Institutional Review Board
LVGE	Left Ventricular Gas Emboli
MFN	Man Flight Number
NASA	National Aeronautics and Space Administration
USSOCOM	United States Special Operations Command
SG	Surgeon General (USAF)
US Navy SAILSS	United States Navy Smart Aircrew Integrated Life Support System
VGE	Venous Gas Emboli